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Dark matter and collider searches in the MSSM

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We study the complementarity between dark matter experiments (direct detection and indirect detections) and accelerator facilities (the CERN LHC and a $\sqrt{s} = 1$ TeV e^+e^- Linear Collider) in the framework of the constrained Minimal Supersymmetric Standard Model (MSSM). We show how non–universality in the scalar and gaugino sectors can affect the experimental prospects to discover the supersymmetric particles. The future experiments will cover a large part of the parameter space of the MSSM favored by WMAP constraint on the relic density, but there still exist some regions beyond reach for some extreme (fine tuned) values of the supersymmetric parameters. Whereas the Focus Point region characterized by heavy scalars will be easily probed by experiments searching for dark matter, the regions with heavy gauginos and light sfermions will be accessible more easily by collider experiments. More informations on both supersymmetry and astrophysics parameters can be thus obtained by correlating the different signals.

Contents

1 Introduction 3
2 Dark matter searches 4
3 Collider searches 8
4 Prospects for Discovery 10
5 Summary-Conclusion 13

1 Introduction

Several astrophysical and cosmological independent measurements point towards the fact that the matter in our universe is dominated by a not yet identified dark component (see e.g. Refs. [1,2,3,4] for reviews). The solution of this problem is very crucial for the understanding of our universe, as it concerns different scales of astrophysics such as galaxy through rotation curves, clusters through X-ray emission and the cosmological scale through CMB anisotropy measurements. The latter point provides the most stringent constraint and gives the total fraction of dark matter in the universe with the best accuracy. Indeed, the recent WMAP [5] results lead to a flat concordance model universe with a relic density of cold dark matter of

$$\Omega_{CDM}h^2 = 0.1126\ ^{+0.0161}_{-0.0181} \text{ at } 95\% \text{ CL}. \tag{1.1}$$

The accuracy of the measurement is expected to increase with future data from the PLANCK satellite [6] and a precision $\Delta\Omega_{CDM}h^2 \sim 2\%$ should be obtained.

An interesting possibility for such a cold dark matter candidate is a bath of long lived or stable Weakly–Interacting Massive Particles (WIMPs) which are left over from the Big Bang in sufficient number to account for a significant fraction of the relic density. Since additional constraints, especially from light element cosmonucleosynthesis, strongly disfavor the possibility that dark matter is composed solely of baryons [7], some form of "non–standard" matter is required.

The Standard Model (SM) of high–energy physics, despite of its success in explaining the data available today, requires an extension to explain the stability of the hierarchy between the weak and the Planck scales, the unification of gauge couplings and the origin of electroweak symmetry breaking. The most plebiscited extension of the model is the Minimal Supersymmetric Standard Model (MSSM) [8,9,10,11]. It predicts the existence of several new particles, the superpartners of SM ones. The lightest supersymmetric particle (LSP) is in most of the MSSM parameter space, a stable, massive, neutral and weakly interacting particle : the lightest neutralino, which is thus an interesting and well motivated dark matter candidate. On the other hand, at future colliders such as the Large Hadron Collider (LHC) and the planned International Linear e^+e^- Collider (ILC), supersymmetric particles are expected to be produced and observed if low energy Supersymmetry (SUSY) is present in nature. However, even if part of the supersymmetric spectrum is unveiled at the LHC for example, the properties of the particles which play a dominant role in the relic density will not be measured directly or precisely. Both types of data (from astroparticle and accelerator physics) are thus needed to extract more complete properties of the underlying supersymmetric model [12].

In constrained MSSM, such as the minimal supergravity model (mSUGRA), the minimization of the one-loop scalar potential leads to the well–known relation between the squares of the superpotential Higgs mass term and the soft–SUSY breaking scalar Higgs masses m_{H_u}, m_{H_d} as well as the ratio of the vacuum expectation values of the two Higgs fields $\tan\beta = v_d/v_u$ and the Z boson mass M_Z,

$$\mu^2 = \frac{\left(m^2_{H_d} + \delta m^2_{H_d}\right) - \left(m^2_{H_u} + \delta m^2_{H_u}\right)\tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2 \tag{1.2}$$

imposed at the SUSY breaking scale defined by the quadratic average of the two top squark masses, $M_{SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$. This condition determines the absolute value of the term μ, leaving its sign as a free parameter of the theory.

The four neutralinos ($\chi_1^0 \equiv \chi, \chi_2^0, \chi_3^0, \chi_4^0,$) are superpositions of the neutral fermionic partners of the electroweak gauge bosons $\tilde{B}^0$ and $\tilde{W}_3^0$ (respectively the B–ino and W–ino fields) and the superpartners of the neutral Higgs bosons $\tilde{H}_u^0$, $\tilde{H}_d^0$ (respectively up and down Higgsinos fields). In the $(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0)$ basis, the neutralino mass matrix is given by

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z\cos\beta\sin\theta_W & m_Z\sin\beta\sin\theta_W \\ 0 & M_2 & m_Z\cos\beta\cos\theta_W & -m_Z\sin\beta\cos\theta_W \\ -m_Z\cos\beta\sin\theta_W & m_Z\cos\beta\cos\theta_W & 0 & -\mu \\ m_Z\sin\beta\sin\theta_W & -m_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}. \tag{1.3}$$

where M_1, M_2 are the bino and wino mass parameters, respectively. This matrix can be diagonalized by a single orthogonal matrix z and we can express the LSP χ (often referred in the following as *the neutralino*) as

$$\chi = z_{11}\tilde{B} + z_{12}\tilde{W} + z_{13}\tilde{H}_d + z_{14}\tilde{H}_u. \tag{1.4}$$

This combination determines the nature, the couplings and the phenomenology of the neutralino. The neutralino is usually called "gaugino–like" if $P \equiv |z_{11}|^2 + |z_{12}|^2 > 0.9$, "Higgsino–like" if $P < 0.1$, and "mixed" otherwise.

Depending on the nature of the neutralino, the WMAP constraint can be fulfilled essentially by bino-$\chi\tilde{\tau}$ coannihilation processes if $m_\chi \sim m_{\tilde{\tau}_1}$, $\chi\chi \xrightarrow{A} b\bar{b}$ annihilation for large $\tan\beta$ values or a light pseudoscalar A boson, and

$\chi\chi \to t\bar{t}$ for a sufficiently Higgsino–like neutralino. In the same time, a non negligible wino component can enhance the annihilation process $\chi\chi \to W^+W^-$ and the $\chi\chi^\pm$ and $\chi^+\chi^-$ coannihilation ones.

In the present work, we will consider neutralino dark matter searches in direct or indirect detection experiments and the prospects of superparticle production at future colliders like LHC or ILC. We will focus on the framework of general supergravity scenarios but with non–universal scalar and gaugino soft–SUSY breaking mass terms.

The outline of the paper is as follows. We first summarize, in section 2, the phenomenology of the different kinds of dark matter searches. Section 3 is dedicated to the prospects for producing and detecting SUSY particles and MSSM Higgs bosons at the LHC and at a high energy e^+e^- collider. In section 4, we present a complementary analysis of each type of signal and the impact of non–universality on the detection potential of all types of experiments. For our computation, we use an interface of the latest released version of the codes SUSPECT [13] for the MSSM particle spectrum, MICROMEGAS [14] for the neutralino relic density, and DARKSUSY [15] for the dark matter detection rates. During the writting of this paper, the authors of [16] and [17] have made similar analyses and reached the same conclusions as those presented here. Related work in a variety of frameworks and dealing with cosmological relic density aspects, present accelerators constraints and/or dark matter searches and/or SUSY searches at future colliders can be found in Refs [18] - [60].

2 Dark matter searches

2.1 Dark matter distribution

The dark matter distribution in the galaxy is a crucial ingredient for all kinds of detection techniques. From N-body simulations, this distribution is commonly parameterized as :

$$\rho(r) = \frac{\rho_0[1+(R_0/a)^\alpha]^{(\beta-\gamma)/\alpha}}{(r/R_0)^\gamma[1+(r/a)^\alpha]^{(\beta-\gamma)/\alpha}} \tag{2.5}$$

where r is the galacto-centric coordinate, ρ_0 is the local (sun neighborhood) halo density, R_0 the solar distance to the galactic center and a a characteristic length. If there is an agreement concerning the behavior at large radii ($\beta \sim 3$), the shape of the possible cusp in the innermost region of the galaxy is not well determined if we consider the discrepancies between simulation results of various groups ($1 \lesssim \gamma \lesssim 1.5$). Furthermore, the studies of systems like low surface brightness galaxies seem to favor flat cores. Moreover, the small radius region behavior can differ strongly depending on the physical assumptions such as baryonic effects on the central dark matter density, supermassive black hole induced spikes, dark matter particle scattering on stars, *etc*... (for discussions, see *e.g.* Refs. [61,62,63,64,65,66]). Finally possible inhomogeneities and substructures could be present, leading to a possible clumpyness of the halo.

In contrast, there is a general agreement on the local density ρ_0 which can be determined for each density profile assuming compatibility with the measurements of rotational curves and the total mass of the galaxy; ρ_0 should range from 0.2 to 0.8 GeV.cm^{-3} (see Ref. [2] for a discussion). For definiteness, our results are presented for $\rho_0 = 0.3$ GeV.cm^{-3} for all the density profiles used in the present analysis. A more controversial topic is the possible link between the dark matter distribution and the total relic abundance. One can rescale the density $\rho(r)$ when the calculated value of $\Omega_\chi h^2$ is smaller than the WMAP lower bound, by assuming that the neutralino could form only a fraction of the total amount of cold dark matter. In this study, however, we will not use this procedure as we will mainly focus on the dependence of the detection rates on the SUSY parameter space for a *given* astrophysical framework. Since the local density enters as a scaling factor in the signal fluxes, the effect of varying ρ_0 or applying this rescaling can be taken into account in a straightforward manner.

2.2 Direct detection

Many underground experiments have been carried out around the world in order to detect WIMP candidates by observing their elastic scattering on target nuclei through nuclear recoil [67]. As pointed out before, the astrophysical dependence on this type of detection technique is weak. Namely, the translation of the detection rates/sensitivities into scattering cross section $\sigma_{\chi-p}$ relies only on the knowledge of the local dark matter density ρ_0. Depending on the spin of the target nuclei, the detection rate is given by the spin dependent ($\sigma^{spin}_{\chi-p}$) or the spin independent ($\sigma^{scal}_{\chi-p}$) neutralino–nucleon elastic cross section. The main contributing diagrams are shown in Fig. 1.

The squark (mainly the first generation $\tilde{u}$, $\tilde{d}$ squarks) exchange contributions are usually suppressed by the squark masses. The spin–independent cross section $\sigma^{scal}_{\chi-p}$ is then driven by neutral CP–even Higgs boson (h, H) exchanges ($\chi q \xrightarrow{h,H} \chi q \propto z_{11(2)}z_{13(4)}$) and the spin–dependent cross section $\sigma^{spin}_{\chi-p}$ by Z boson exchange ($\chi q \xrightarrow{Z} \chi q \propto z^2_{13(4)}$).

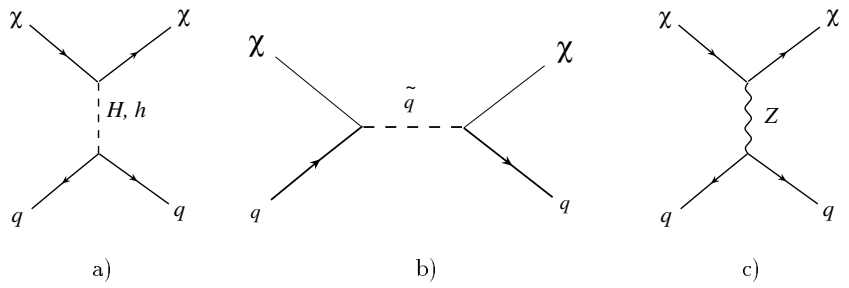

Fig. 1. Feynman diagrams of the processes occuring in direct detection of the lightest neutralinos: a) and b) spin independent processes ($\sigma^{scal}_{\chi-p}$); b) and c) spin dependent processes ($\sigma^{spin}_{\chi-p}$).

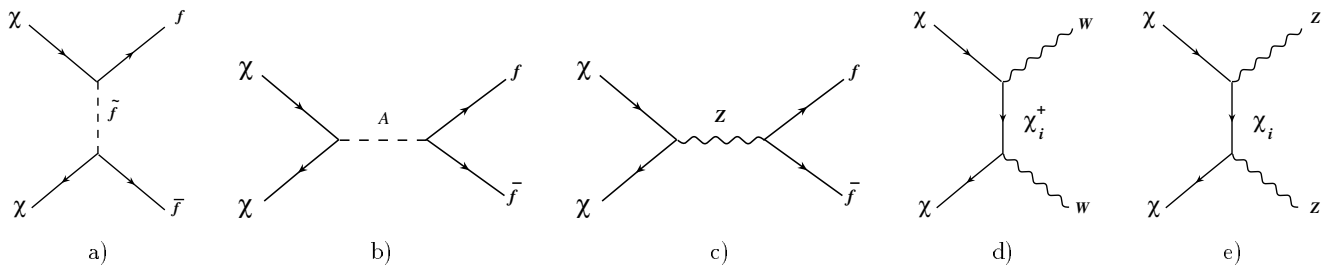

Fig. 2. Feynman diagrams for the dominant channels contributing to neutralino annihilation into SM particles.

Direct detection is thus more favored for a mixed gaugino-Higgsino neutralino and models where the scalar Higgs boson H is sufficiently light.

In the usual mSUGRA scenario, where the soft terms of the MSSM are assumed to be universal at the unification scale, the spin–independent cross section turns out to be constrained by $\sigma^{scal}_{\chi-p} \lesssim 3 \times 10^{-8}$ pb [4]. However, it has been shown that if the assumption of universality in the scalar and/or gaugino sectors is relaxed, the cross section can be increased significantly with respect to the universal scenario and could values of the order of reach $\sigma^{scal}_{\chi-p} \sim 10^{-6}$ pb [28,29,30,31]. QCD corrections to the neutralino-nucleon scattering cross sections can also be relevant [68].

Current experiments such as EDELWEISS [69] and CDMS [70] are sensitive to WIMP–proton cross sections larger than approximately 10^{-6} pb, excluding the DAMA region [71]. These sensitivities are slightly too small to probe minimal SUSY models if we impose the accelerator constraints and the bound on the relic density from WMAP. Several new or upgraded direct WIMP detection experiments will soon reach a significantly improved sensitivity (GENIUS, EDELWEISS II [72], ZEPLIN(s) [73], CDMS II and superCDMS [74]). The next generation of experiments (*e.g* EDELWEISS II and CDMS II) will lead to a minimum of the valley sensitivity around 10^{-8} pb for a neutralino mass of $m_\chi = \mathcal{O}(100$ GeV). Though challenging from the experimental point of view, a ton-size detector (ZEPLIN, SuperCDMS) should be able to reach $\sigma^{scal}_{\chi-p} \gtrsim 10^{-10}$ pb which would be conclusive to probe WIMP dark matter models. In our study, we will take the neutralino mass dependent projected experiment sensitivities of EDELWEISSII [72] and ZEPLIN [73].

2.3 Gamma Indirect detection

Dark matter can also be observed through its annihilation products in the galactic halo. In particular, the annihilation in the Galactic Center (GC) where the dark matter density is important could lead to large fluxes and promising experimental signals, even if the exact behavior in the central region is poorly constrained. Unfortunately, the astrophysical uncertainties dominate largely the ones coming from particle physics models, affecting considerably the prospects of discovery in gamma indirect detection experiments.

The main annihilation processes entering in the calculation of gamma–ray fluxes from the GC are depicted in Fig. 2. The large masses of the scalar fermions and their small Yukawa couplings usually suppress the contribution of the diagrams with t–channel sfermions exchange. The dominant cross sections are thus $\sigma(\chi\chi \xrightarrow{A} b\bar{b}) \propto [z_{11(2)} z_{13(4)}]^2$, $\sigma(\chi\chi \xrightarrow{Z} t\bar{t}) \propto [z^2_{13(4)}]^2$ and $\sigma(\chi\chi \xrightarrow{\chi^+(\chi^0_j)} W^+W^-(ZZ)) \propto [z_{13(4)} V_{12}]^2$ and/or $[z_{12} V_{11}]^2$ ($[z_{13(4)} z_{j3(4)}]^2$), with V_{ij} the chargino mixing matrice. Annihilation in these channels are favored for wino–like or Higgsino–like neutralino. The resulting observed differential gamma–ray flux at the Earth coming from a direction forming an angle ψ with respect

to the GC is

$$\frac{d\Phi_\gamma(E_\gamma,\psi)}{d\Omega dE} = \sum_i \frac{1}{2}\frac{dN_\gamma^i}{dE_\gamma}\langle\sigma_i v\rangle \frac{1}{4\pi m_\chi^2}\int_{\text{line of sight}} \rho^2\left(r(l,\psi)\right) dl \tag{2.6}$$

where the discrete sum is over all dark matter annihilation channels, dN_γ^i/dE_γ is the differential gamma–ray yield and $\langle\sigma_i v\rangle$ is the annihilation cross section averaged over the velocity distribution. It is customary to isolate the dependence on the halo dark matter model with respect to particle physics, defining the dimensionless quantity (see Ref. [75,76])

$$\bar{J}\left(\Delta\Omega\right) = \frac{1}{8.5\,\text{kpc}}\left(\frac{1}{0.3\,\text{GeV/cm}^3}\right)^2 \int_{\Delta\Omega}\int_{\text{line of sight}} \rho^2\left(r(l,\psi)\right) dl d\Omega\,. \tag{2.7}$$

in a solid angle $\Delta\Omega$ centered on $\psi = 0$.

As pointed out before, a crucial ingredient for the calculation of the annihilation fluxes is the density profile of dark matter around the core of the GC. In the present work, we choose the intermediate NFW halo profile [77] ($\gamma = 1$, $\bar{J}_{NFW}(\Delta\Omega = 10^{-3}) \sim 10^3$). One can rescale fluxes to have results for other commonly used profiles either with a stronger cusp like the one proposed by Moore et al. [78] ($\gamma = 1.5$, $\bar{J}_{Moore}(\Delta\Omega = 10^{-3}) \sim 10^5$) or shallower slope like the one proposed by Kravtsov et al. [79] ($\gamma = 0.4$, $\bar{J}_{Kravtsov}(\Delta\Omega = 10^{-3}) \sim 10$)[1]. The sensitivity of such variations in the dark matter profile on the experimental prospects will be illustrated later; see Figs. 10c) and d). In the literature, some authors [76] also consider as input parameter of the theory a *boost factor* acting on $\bar{J}$, to take into account possible halo inhomogeneities (clumps for instance).

Recently several experiments have detected a significant ammount of gamma–rays from the galactic center region. Observations by INTEGRAL [80] and EGRET [81] have revealed γ–ray emission from this region although no corresponding sources have been identified so far. The VERITAS [82] and CANGAROO [83] collaborations using, respectively, the Whipple 10 meters and CANGAROO–II atmospheric Cerenkov Telescopes (ACTs) have independently detected TeV γ–rays from the same region. Finally, HESS [84] claims to have observed a signal corresponding to a WIMP in the multi–TeV energy range. Here, we refrain from interpreting all these signals as due to dark matter annihilation. Although an explanation in terms of a heavy dark matter particle like the LSP neutralino [53,54,84] is possible for each signal (except for INTEGRAL, see for instance Ref. [85] for a light dark matter scenario proposal), these measurements are not compatible with each other and cannot be explained by a single scenario. Moreover, purely astrophysical interpretations of these signals are possible [86,87].

In any case, considering the uncertainties in the computations and that alternative astrophysical interpretations are possible [86,87], it is reasonable not to attribute these signals to a neutralino and proceed with our prospective analysis in the SUSY parameter space. Nevertheless, the EGRET signal ($\sim 4\times10^{-8}$ γ cm^{-2}s^{-1}) can be seen as an upper bound even if one has to keep in mind that it may not arise exactly from the galactic center [88]. We will also consider the sensitivities of the HESS [89] and GLAST [90] experiments (respectively 10^{-12} γ cm^{-2}s^{-1} with a 100 GeV threshold and 10^{-10} γ cm^{-2}s^{-1} with a 1 GeV threshold) as a probing test of our models. The neutralino mass dependent integrated sensitivities that we use in our analysis can be found in Ref. [91].

2.4 Neutrino Indirect detection

Dark matter particles of the halo can also be trapped in astrophysical bodies (like the Sun) by successive elastic diffusion on its nuclei (hydrogen) during the age of the target object ($\sim 10^{10}$ years). This leads to a captured population which annihilates, producing neutrino fluxes that can be detected by a neutrino telescope, signing the presence of dark matter in the storage object direction. The annihilation rate at a given time t can be written [92]:

$$\Gamma_A = \frac{1}{2}C_A N_\chi^2 = \frac{C}{2}\tanh^2\sqrt{CC_A}t, \tag{2.8}$$

Where C is the capture rate which depends on the local density ρ_0 and on the neutralino-proton elastic cross section. $\Gamma_A \approx \frac{C}{2} = cste$ when the neutralino population has reached equilibrium, and $\Gamma_A \approx \frac{1}{2}C^2C_At^2$ in the initial collection period. When accretion is efficient, the annihilation rate follows the capture rate C and thus the neutralino-quark elastic cross section, whereas only the differential spectrum depends on the annihilation processes. The flux is then given by

$$(\frac{d\Phi_\nu}{dE_\nu}) = \frac{\Gamma_A}{4\pi R^2}\sum_F B_F\frac{dN_\nu^F}{dE_\nu}(E_\nu) \tag{2.9}$$

[1] For $\gamma \geq 1.5$, $\bar{J}$ diverges and one has to regularize the integral of eq. 2.7.

where F labels the annihilation final states and R is the Sun-Earth distance. As related to the local dark matter density, the astrophysical dependence is weak, similarly to the direct detection case. One should notice that the collection of neutralinos is time dependent such that the trapped population can have been enhanced if the Sun has been flying in some clumps during its history.

The particle physics behavior is dominated by the capture rate driven by $\sigma_{\chi-p}$. The dominant processes are shown on Fig. 1 (spin dependent for the Sun because of the non zero hydrogen nucleus spin). The couplings have already been described in the section related to direct detection. The diagrams driving annihilation (see Fig. 2) and their couplings have been discussed in the section devoted to gamma indirect detection. For our prospect we will consider the fluxes coming from the Sun which is favored for neutralinos with a non negligible Higgsino component. Indeed the Z exchange is then allowed in the neutralino-quark diffusion and the resulting flux can be high. The annihilation can also enhance the flux, especially by giving harder neutrino spectra when the Higgsino and/or the wino fraction are not negligible leading to $t\bar{t}, W^+W^-$ final states instead of $b\bar{b}$ for a dominant bino neutralino [29, 93].

The Earth could be another possible source but the resulting fluxes are beyond reach of detection [93]. The neutralino annihilations in the galactic center can also lead to neutrino fluxes ($i = \nu$ in equation 2.6) but the gamma flux expectations are much more promising with regard to experiment sensitivities [94].

Present experiments like MACRO [95], BAKSAN [96], SUPER K [97] and AMANDA [98] (which size and place disfavors detection of horizontal flux coming from the Sun) give limits on possible fluxes around 10^4 μ km^{-2}yr^{-1}. Future neutrino telescopes like ANTARES [99] or a km^3 size like ICECUBE [100] will be able to probe respectively around 10^3 and 10^2 μ km^{-2} yr^{-1}. We used neutralino mass dependent sensitivities of reference [101] for ANTARES and [102] for ICECUBE.

2.5 Positron Indirect detection

Neutralino annihilations in the halo can also give rise to measurable positron fluxes. Positrons being charged particles interact during their propagation such that the directional information is lost. Furthermore those interactions imply that the observed positrons do not come from far away in the galaxy. In addition to the variability of the density profile which is a possible source of uncertainties at the production level, the understanding of the propagation taking into account interactions with magnetic fields, inverse Compton and synchrotron processes is the most relevant and difficult question to control in order to be able to understand measurement or/and to estimate positron spectra. The positron flux results from the steady state solutions of the diffusion-loss equation for the space density of cosmic rays per unit energy, $dn/d\varepsilon$:

$$0(= \frac{\partial}{\partial t}\frac{dn}{d\varepsilon}) = \boldsymbol{\nabla} \cdot \left[K(\varepsilon, \boldsymbol{x})\boldsymbol{\nabla}\frac{dn}{d\varepsilon}\right] + \frac{\partial}{\partial \varepsilon}\left[b(\varepsilon, \boldsymbol{x})\frac{dn}{d\varepsilon}\right] + Q(\varepsilon, \boldsymbol{x}), \tag{2.10}$$

where K is the diffusion constant (assumed to be constant in space throughout a "diffusion zone", but it may vary with energy), b is the energy loss rate and Q is the source term (see [45] for details). We take [103]

$$K(\varepsilon) = 3.3 \times 10^{28}\left[3^{0.47} + \varepsilon^{0.47}\right] \text{ cm}^2 \text{ s}^{-1}. \tag{2.11}$$

and [104]

$$b(\varepsilon)_{e^+} = 10^{-16}\varepsilon^2 \text{ s}^{-1}, \tag{2.12}$$

which results from inverse Compton scattering on both the cosmic microwave background and diffuse starlight. The diffusion zone is a slab of thickness $2L$ (L= 4 kpc to fit observations of the cosmic ray flux, see [42] and references therein. Variations of the propagation parameters may modified the computation results by around an order of magnitude (see [46]). The source term $Q = f(\rho(r), \langle\sigma v\rangle)$ can be modified if one considers the presence of clumps in the (quite local) dark matter distribution and a possible resulting multiplying boost factor $b \lesssim 10$ [47]. The particle physics dependence also enters in the source term and comes from the supersymmetric parameter influence on annihilation cross section (see Fig. 2 and section 2.3).

The HEAT experiment, in three flights which have taken place in 1994, 1995 and 2000, observed a flux of cosmic positrons in excess of the predicted rate, peaking around 10 GeV [105]. This signal can be accommodated by neutralino annihilation but requires a boost factor [48, 46]. Furthermore the HEAT measurement uncertainties in the 30 GeV bin are quite large. We thus consider in this work the estimated fluxes with regard to the future experiments AMS-02 and PAMELA. The exact positron spectrum depends on annihilation final states, dark matter distribution and propagation parameters (see [46]) but as a reasonable approximation for our prospect, one can consider the spectra being peaked around $M_\chi/2$. At those energy, we checked that the background of reference [106] can be fitted by $E^2 d\Phi_{e^+}/d\Omega dE \simeq 1.16 \times E^{-1.23}$. Following references [23] and [60] we require as a benchmark condition : $\frac{\phi_\chi^{e^+}}{\phi_{Bckgd}^{e^+}}|_{m_\chi/2} \sim 0.01$ (See [16] for more precise criteria)

2.6 Antiproton Indirect detection

Another possible signal of dark matter may be the detection of antiproton fluxes produced by neutralino annihilation. To calculate those fluxes we need to solve a propagation equation for antiprotons [49, 103, 106, 107, 108, 109]. This includes spatial diffusion in the disk and the halo, K_x scaling with the rigidity (momentum per unit of charge, $R = p/Z$) as $K_0 R^\delta$. The galactic wind, with a speed V_c, imply convection effects deflecting antiproton away from the disk. Collisions with interstellar matter (hydrogen and helium) and Coulomb losses modify the energy distribution. Reacceleration by Fermi shocks on magnetic fields could be taken into account by a diffusion coefficient K_p related to the spatial diffusion K_x and the Alven velocity of disturbances in the plasma, V_A. We used the diffusion model [49] of the DarkSusy package with the diffusion–convection [106] option,

$$\boldsymbol{\nabla} \cdot \left[K_x \boldsymbol{\nabla} \frac{dn}{d\varepsilon} \right] - \boldsymbol{\nabla} \cdot \left[\boldsymbol{V_c} \frac{dn}{d\varepsilon} \right] - n^H v_{\bar{p}}(\varepsilon) \sigma_H^{in}(\varepsilon) \frac{dn}{d\varepsilon} + Q(\varepsilon, \boldsymbol{x}) = 0, \tag{2.13}$$

with $\delta = 0.6$, $V_c = 10$ km.s^{-1}, $K_0 = 25 \times 10^{27}$ cm^2 s^{-1}. n^H is the interstellar Hydrogen density number, $v_{\bar{p}}$ is the antiproton velocity and σ_H^{in} is the inelastic antiproton–hydrogen cross section. Antiprotons propagate on longer distance than positrons. The resulting flux is thus slightly more sensitive to the dark matter distribution in the galaxy, and especially in its central region. The antiproton flux can be expressed as

$$\phi_{\bar{p}}(R_0, T) = b \ \langle \sigma v \rangle \sum_i \frac{dN^i}{dT} B^i \left(\frac{\rho_0}{m_\chi} \right)^2 \ C_{\rm prop}(T) \tag{2.14}$$

where T is the $\bar{p}$ kinetic energy, $C_{\rm prop}(T)$ contains propagation effect, and b is a possible boost factor resulting from halo clumpyness. Experiments like BESS and CAPRICE measured the antiproton flux. The signal can be fitted by the astrophysical background antiproton flux and seems to be peaked at 1.76 GeV around 2×10^{-6} $\bar{p}$ cm$^{-2} s^{-1} sr^{-1}$. The measurement at 37.5 GeV seems to suggest an excess compared to the models. We estimated the antiproton fluxes from neutralino annihilation at those two energy for which the diffusion dependence is weaker than for the low energy part of the spectrum. Following [16], we will show as a benchmark region where $\phi_{\bar{p}}(R_0, 1.76) > 2 \times 10^{-7}$ $\bar{p}$ cm$^{-2} s^{-1} sr^{-1}$ checking also the value at 37.5 GeV.

3 Collider searches

3.1 Constraints

3.1.1 The mass spectrum constraints.

We have implemented in our analysis the lower bounds on the masses of SUSY particles and of the lightest Higgs boson. In the squark and slepton sector parameters leading to tachyons are excluded. We applied the LEP2 lower bound limit on the mass of the lightest chargino $m_{\chi_1^+} > 103.5$ GeV [110]. Typically, the most constraining bound comes from the lightest Higgs boson mass limit. In the decoupling regime ($m_A \gg M_Z$, valid in all our parameter space), $m_h > 114.4$ GeV [111]. It is well known than the theoretical prediction of the Higgs mass is very sensitive to the value of the top mass. The radiative corrections used for the calculation of the higgs mass are very well described in [113]. To take into account this sensitivity in the analysis, we have used $m_t = 175$ GeV but we illustrate the dependance of our result on the top mass (178 to 182 GeV) in Fig. 10b [112].

3.1.2 The $b \to s\gamma$ branching ratio.

One observable where SUSY particle contributions might be large is the radiative flavor changing decay $b \to s\gamma$ [114]. In the Standard Model this decay is mediated by loops containing the charge 2/3 quarks and $W-$bosons. In SUSY theories additional contributions come from loops involving charginos and stops, or top quarks and charged Higgs bosons. The measurements of the inclusive decay $B \to X_s \gamma$ at CLEO [115] and BELLE [116], lead to restrictive bounds on the branching ratio $b \to s\gamma$. The experimental value for the branching ratio of the process $b \to s\gamma$ is $(3.52 \pm 0.30) \times 10^{-4}$ [117]. Including theoretical errors [118] (0.30×10^{-4}) coming from its prediction by adding the two uncertainties in quadrature, we impose $2.33 \times 10^{-4} \leq BR(b \to s\gamma) \leq 4.15 \times 10^{-4}$, at the 3σ level. Typically, the $b \to s\gamma$ is more important for $\mu < 0$, but it is also relevant for $\mu > 0$, particularly when tanβ is large.

3.1.3 The anomalous moment of the muon.

We have also taken into account the SUSY contributions to the anomalous magnetic moment of the muon, $\delta a_\mu = a_{susy} - a_{SM}$ [120]. We used in our analysis the recent experimental results [121], as well as the most recent theoretical evaluations of the Standard Model contributions [122]. An excess of about 2.7 sigmas between experiment and theory is found when e^+e^- data are used to estimate a_{SM}, leaving room for a SUSY contribution of $a_{susy} = (25.2 \pm 9.2) \times 10^{-10}$, or, at the two sigma level, $6.8 < a^{10}_{susy} < 43.6$. Such a contribution favors $\mu > 0$ and rather light sleptons and gauginos. However, this slight discrepancy is smaller if tau data are used instead to evaluate a_{SM}. We therefore do not restrict the parameter space with the δa_μ constraint, but show the relevant contour $a_{SUSY} = 6.8 \times 10^{-10}$ instead.

3.1.4 The $B_s \to \mu^+\mu^-$ branching ratio.

Finally, we have considered the limit [123] on the $B_s \to \mu^+\mu^-$ branching ratio [124]. The upper bound on this process $\mathrm{B}(B_s \to \mu^+\mu^-) < 2.9 \times 10^{-7}$ does not constrain the parameter space of mSUGRA. However it has been stressed recently that for non-universal soft terms the constraint can be very important [125,126], especially for large $\tan\beta$ and low values of the Higgs masses. There is also a strong correlation between the $B_s \to \mu^+\mu^-$ branching ratio and cross sections for direct [126] and indirect [53] detection of dark matter.

3.2 LHC

The LHC is a pp collider with center of mass energy of $\sqrt{s} = 14$ TeV which is expected to start in 2007. Hadronic colliders produce mainly colored particles like squark pairs $\tilde{q}\tilde{q}$, squark anti-squark $\tilde{q}\tilde{q}^*$, gluino pairs $\tilde{g}\tilde{g}$ or associated squark–gluino production $\tilde{q}\tilde{g}$:

$$
\begin{array}{l}
q\overline{q},\ gg \to \tilde{q}\tilde{q}^* \\
qq \to \tilde{q}\tilde{q} \\
q\overline{q},\ gg \to \tilde{g}\tilde{g} \\
qg \to \tilde{q}\tilde{g}
\end{array}
$$

The $\tilde{q}\tilde{q}$ final state requires initial state of the form $q\overline{q}$ or gg whereas squark pair are only produced from qq state. Gluino pairs come from $q\overline{q}$ and gg states and the squark–gluino are only produced via quark–gluon collisions. Cross sections for squark and gluino productions are very high at LHC, e.g. for $m_{\tilde{q}} = m_{\tilde{g}} = 500$ GeV, $\sigma(\tilde{q} - \tilde{g}) \sim 62$ pb. For an integrated luminosity of 100 fb^{-1}, corresponding to one year of LHC running at high luminosity, 6.2 millions squark-gluino pairs are thus expected to be produced, leading to a "fast" (assuming detectors are well understood) discovery and to hints on the underlying SUSY model. Off course, for heavier spectrum, cross sections will be lower, but in any case, the production of squarks and gluino at the LHC, if kinematically allowed, should be important.

The decays of squarks and gluinos lead to multi-jets + isolated leptons + missing E_T signals. We consider the exclusion limits of reference[127] which establish that squarks and gluinos could be detected up to $m_{\tilde{q}-\tilde{q}} \sim 2 - 2.5$ TeV for the first two generations of squarks, which nearly corresponds to the parton-parton kinematics limit is roughly 14/3 TeV. The detection of the third generation of squarks (sbottom $\tilde{b}_1$ and stop $\tilde{t}_1$) appears to be more difficult in hadronic collider due to their special decay modes [128].

3.3 Sparticle production in e^+e^- colliders.

We also analyzed the prospects for producing SUSY particles and heavy Higgs bosons at high–energy and high luminosity e^+e^- colliders [129]. In this exploratory study we will assess the accessibility of certain production modes simply through the corresponding total cross section, without performing any background studies. However, in most cases the clean experimental environment offered by e^+e^- colliders should allow discovery of a certain mode, given a sample of a few dozen events. Difficulties might arise in some narrow regions of parameter space, which we will point out in the following discussion. We have taken the example of a future International Linear Collider (ILC) with center of mass energy of 1 TeV and an integrated luminosity of 500 fb^{-1}. We will consider a given channel to be visible if its total cross section exceeds $\sigma_{\min} = 0.1$ fb, which correspond to a sample of 50 signal events per year.
In our study, we will consider the following production processes, shown on Fig. 3.

$$
\begin{array}{l}
e^+e^- \to \tilde{l}\tilde{l}^* \text{ (mainly } \tilde{\tau}\tilde{\tau} \text{ and } \tilde{\nu}\tilde{\nu}) \\
e^+e^- \to \chi^+\chi^- \\
e^+e^- \to \chi\chi_2^0 \\
e^+e^- \to HA,
\end{array}
$$

Concerning the sleptons, pairs of $\tilde{e}^{\pm}_{R,L}$ are produced via s–channel photon and Z boson exchange and the t– channel exchange of the four neutralinos χ^0_i. Since the electron–Yukawa coupling is suppressed, only the gaugino fraction of the neutralinos exchanged contributes to the process. Thus the influence of the soft breaking gaugino masses M_1 M_2 and μ through M_{H_u} will be important in the production cross section. The main final state will be the lightest state, $\tilde{e}_R$, as in supergravity models, the $\tilde{e}_R - \tilde{e}_L$ mass difference can be important. For the third generation of slepton, the production proceeds only via γ and Z boson exchange. In this case, we will only concentrate on the production of the lightest state, $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$ which offers the largest possibilities of discovery. A look at the formulas in the appendix of [21] shows a strong dependence of the cross section on the selectron velocity β : only sleptons with masses of several GeV below the kinematical limit can be observed[2]. Note that it is also possible to produce and observe sleptons through their decay even if $m_{\tilde{l}} > \sqrt{s}/2$ [130].

Due to the couplings and the kinematics, the sleptons will mainly decay into their leptonic partners and the gaugino–like neutralinos or charginos (if allowed). In other words, the regions of low values of μ with Higgsino–like $\chi^0_{1,2}$ and χ^+_1 will be a blind region for the detection of sleptons. Whereas the lighter $\tilde{e}_R$ will predominantly decay following $\tilde{e}^{\pm}_R \to e^{\pm}\chi^0_1$, the heavier left handed $\tilde{e}_L$ will decay into wino–like chargino $\chi^{\pm}_1$ or neutralino χ^0_2 because these processes occur via the SU(2) coupling, much stronger than the $\mathrm{U(1)_Y}$ involved in $\tilde{e}^{\pm}_R \to e^{\pm}\chi^0_1$.

The charginos are produced through s–channel photon and Z boson exchange as well as t–channel sneutrino exchange (see Fig. 3). Note that the sneutrino channel contributes with an opposite sign (see [21]) to the s–channel diagrams. The production will thus be maximized in regions of heavy sneutrinos and for Higgsino–like charginos ($|\mu| \ll M_2$). For light sneutrino the destructive interference can affect considerably the cross section whereas productions of Higgsino–like charginos are mainly insensitive to $m_{\tilde{\nu}}$ (the $\tilde{\nu}e\chi\pm_1$ coupling vanish in this case). In any case, the cross section is usually rather large, making productions possible for masses up to the kinematical threshold region.

For M_2, $|\mu| <$ scalar/sleptons masses, the chargino is the lighter charged sparticle and mainly decay into χ^0_1 W, with the W decaying into a ff' pair with a known branching ratio. For small slepton masses, virtual slepton exchange can enhance other processes leading to only $\tau^{\pm}\nu_{\tau}\chi^0_1$ final states [131]. For large values of tanβ, charged Higgs boson exchange contribution can also enhance the branching fraction for the τ final state.

The production of the lightest neutralinos $\chi^0_{1,2}$ occurs via s–channel Z boson exchange and t– or u–channel $\tilde{e}_L$, $\tilde{e}_R$ exchanges. A gaugino–like neutralino does not couple to the Z boson. However, a high Higgsino fraction leads to an enhancement of the $Z\chi^0_1\chi^0_2$ coupling and a suppression of the $e\tilde{e}_{L,R}\chi^0_{1,2}$ one proportional to the gaugino fraction of the neutralinos. Except in the extreme Higgsino limit, the cross section is much smaller than the chargino one (whose nature ensures a reasonable production rate for gaugino–like of Higgsino–like charginos through Z exchange).

The decay modes of the χ^0_2 depends strongly on the SUSY parameter space, and can be completely leptonic (if the two–body decay $\chi^0_2 \to l^{\pm}\tilde{l}^{\mp}$ is the main process) or hadronic (if $\chi^0_2 \to h\chi^0_1$ is dominant). However, at an e^+e^- collider, hadronic χ^0_2 decays are as easy to sign as the leptonic ones. The only difficulty will be in regions of the parameter space where the mass difference $m_{\chi^0_2} - m_{\chi^0_1}$ is small, where χ^0_2 decays almost exclusively into quasi–invisible modes.

If the pseudoscalar mass is sufficiently heavy (around $\sim$ 200 GeV depending on tanβ) the model is in the so–called decoupling regime [132], where the masses of the scalar H and pseudoscalar A (and even $H^{\pm}$ for larger m_A) are almost degenerate. In this limit, both the (tree–level) coupling of the A and the H to massive vector bosons are suppressed, as the ZAh one. The only important Higgs production process becomes thus the associated HA production through Z boson exchange in the s–channel (see Fig. 3) [132]. In any case, the cross section is suppressed by the kinematical β^3 factor near the threshold.

If $m_A < 2m_t$ or $\tan^2\beta > m_t/m_b$, the heavy scalar Higgs boson H and pseudoscalar A will mainly decay into $b\overline{b}$ and $\tau\overline{\tau}$ pairs [132]. If the $t\overline{t}$ channel is kinematically open and for lower values of tanβ, the process $A/H \to t\overline{t}$ dominates the decay modes. In some region of the parameter space, decays into SUSY particles are possible. These modes will be more difficult to analyze in the framework of an e^+e^- collider but the signals should be clear enough to be detectable [133].

We draw attention to the fact that we did not include ISR in our calculation but check its weak relative importance for the focus of the present work with regard *e.g* to astrophysical uncertainties.

4 Prospects for Discovery

Using the theoretical, experimental and cosmological constraints discussed in the previous sections, we perform a full scan of the (m_0, $m_{1/2}$) plane for a given value of tanβ and A_0, fixing the Higgsino parameter μ to be positive. The results are illustrated in Figs. 4 to 9 which show the regions allowed by the different constraints we imposed in universal (Fig. 4, 5), gaugino non–universal (Fig. 6, 7), and scalar non–universal (Fig. 8, 9) scenarios. We present also the regions of the parameter space which will be accessible in a near future for typical experiments of the different kinds

[2] We can also see it at the natural cross section suppression of spin 1 $\to$ spin 0 spin 0 processes

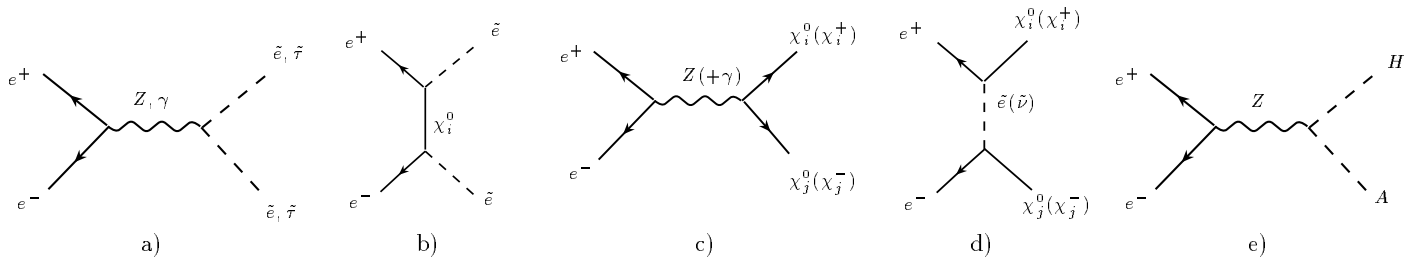

Fig. 3. Production processes for a Linear Collider.

of detection discussed above. The influence of other external free parameters (m_t and galactic profiles) is illustrated in Fig. 10.

The areas excluded or disfavored by the experimental constraints are shown in grey. For the anomalous moment of the muon, the black dashed lines corresponds to $\delta a_\mu = 6.8 \times 10^{10}$ which decreases in the direction of increasing m_0. The cosmologically favored relic density range $0.03 < \Omega_\chi h^2 < 0.3$ is shown in yellow (very light grey) and the WMAP [5] constraint, Eq.(1.1) is the internal black region inside the yellow (very light grey) area. Our starting parameter space is the Universal mSUGRA/CMSSM plane, where one assumes a unified gaugino and scalar mass at the GUT scale ($m_{1/2}$ and m_0 respectively). We first choose $A_0 = 0, \tan\beta = 35, \mu > 0$ and perform a full scan of the (m_0, $m_{1/2}$) plane : $0 < m_0 < 6000$ GeV, $0 < m_{1/2} < 2000$ GeV . We will then point out the effects of non universal mass terms in gaugino and Higgs sectors (wino mass $M_2|_{GUT}$, gluino $M_3|_{GUT}$, up-type Higgs mass $M_{H_u}|_{GUT}$ and down-type Higgs mass $M_{H_d}|_{GUT}$) as well as $\tan\beta$ and m_t.

4.1 Universal case

For intermediate values of $\tan\beta$, there are mainly two regions leading to a favored neutralino relic abundance. The first one is at low m_0 where the lighter stau $\tilde{\tau}_1$ is almost degenerate with the neutralino, and the $\tilde{\tau}_1\chi$ as well as $\tilde{\tau}_1\tilde{\tau}_1$ co–annihilations are efficient enough to reduce the relic density. The second one is along the boundary where the electroweak symmetry breaking cannot be achieved radiatively (Hyperbolic Branch/Focus Point (HB/FP): high m_0 corresponding to a low μ). In this region the neutralino is mixed bino-Higgsino, enhancing $\chi\chi$ annihilation through Z exchange and $\chi\chi_1^+, \chi\chi_2^0$ coannihilations. Those two regions are generically thin and fine tuned. Direct detection experiments are then favored for light Higgs scalar H (mainly low $m_0, m_{1/2}$) or around the HB/FP region where the Higgsino fraction is sufficient to increase significantly the scattering cross section on the nucleus and allow an observation in an experiment like ZEPLIN (see Fig. 4a). Concerning indirect detection with neutrino telescopes, a significant signal from the Sun requires a large Higgsino fraction to enhance the spin dependent interaction $\chi q \xrightarrow{Z} \chi q$. This can only take place in the HB/FP branch where a km^3 size detector like ICECUBE will be able to probe models satisfying the WMAP constraint (see Fig. 4b).

Gamma indirect detection of neutralino in the galactic center requires efficient annihilation cross section. The possible processes are either $\chi\chi \xrightarrow{A} b\bar{b}$ which is favored in region where the pseudo–scalar A is light (low $m_0, m_{1/2}$), or/and when the $\chi\chi A$ coupling ($\propto z_{11(2)} z_{13(4)}$) is enhanced through the Higgsino fraction in the HB/FP branch. In this region, the annihilation process $\chi\chi \xrightarrow{Z} t\bar{t}$ is also favored since the $\chi\chi Z$ coupling is proportional to $z^2_{13(4)}$. This zone is within reach of the HESS telescope and will be covered by future satellite like GLAST as we can clearly see in Fig 4c. This figure should be compared to Fig. 10c and 10d to keep in mind the importance of the halo profile assumption we made. The positron and antiproton fluxes have essentially the same particle physics dependence than the gamma–ray fluxes through the annihilation cross section factor $\langle\sigma v\rangle$. The favored region for positron and antiproton are thus also located where the neutralino annihilation is strong and an experiment of the type of PAMELA should be able to detect any signal from this region for a sufficiently large boost factor (see Figs. 4e and 4f).

Prospects for producing SUSY particles and heavier Higgs bosons at future colliders is shown on Fig. 4 d). LHC will be efficient in the parameter space where the particles charged under SU(3) are light : light squarks $\tilde{q}$ (low m_0 values $\lesssim 2-2.5$ TeV) and/or light gluinos $\tilde{g}$ (small M_3 $i.e$ $m_{1/2} \lesssim 1000$). A future 1 TeV Linear Collider can probe the slepton sector for light $\tilde{l}$ ($m_0 \lesssim 700$ GeV, $m_{1/2} \lesssim 1000$ GeV). The $\chi\chi_2^0$ (mainly bino and wino respectively) production is also favored for low m_0 through selectron exchange but decreases when $m_{\tilde{e}}$ (mainly m_0) increases up to $m_0 \sim 2000$ GeV where the Higgsino fraction of the neutralinos allows the Z exchange along the EWSB boundary. The chargino production follows first the kinematics limit of wino chargino production ($m_{1/2} \sim 600$ GeV, $2m_{\chi_1^+} \simeq 2 \times 0.8 \times m_{1/2} \simeq 1$ TeV) and then reaches higher $m_{1/2}$ values thanks to the Higgsino component of χ_1^+ along the EWSB boundary at

high m_0. The region which can give a sufficiently high rate of HA production is restricted to the lower left corner of the plane and is already experimentally excluded.

Non zero value for the trilinear coupling A_0 term mainly affects third generation sfermion masses through its splitting. Thus, it has not direct consequences for dark matter searches like direct detection and neutrino indirect detection for which essentially first generation of quark–squarks coupling from proton scattering are involved. Annihilation can be enhanced with a positive non–zero value of the trilinear coupling through $\tilde{\tau}, \tilde{b}, \tilde{t}$ exchange which can be of interest for $\gamma, e^+, \bar{p}$ indirect detection.
It can also favored $\chi\tilde{\tau}$ ($\chi\tilde{b}$,$\chi\tilde{t}$) coannihilations processes. Those region are difficult for dark matter searches but can be reach for favorable astrophysics scenario. If the extreme case, $\chi\tilde{q}$ coannihilation region leads to signal difficult to be detected at LHC (essentially missing E_T and few jets) but on the other hand the possibility of lighter squarks ($\tilde{b}$ or $\tilde{t}$) can favor the LHC perspectives, especially in the low m_0 region. Such trilinear mixing also favors a discovery at a 1 TeV Linear Collider through the production of lighter stau at low m_0. We should notice here also that $A_0 = m_0$ pushes away focus point region.

The value of m_t is also essential for the position or the existence of this region which strongly depends on the top Yukawa coupling. We show the relic density and collider situation for $m_t = 178$ and 182 GeV on Fig.10a and 10b respectively. For $m_t = 178$ GeV, one needs to extend the m_0 range up to 9 TeV to get the no EWSB boundary, but it is not enough for $m_t = 182$ GeV where we can find this region but for even larger values of m_0 (around 20 TeV) re–opening the question of fine tuning. As a consequence, the range shown on Fig.10b does not contain any region with interesting relic density. Considering the collider capabilities, the gaugino chargino/neutralino concerned regions are extended as the Higgsino region is pushed away or absent.

High value of $\tan\beta$ (~ 50) leads to light Higgses A, H. This can open a Higgs funnel which decreases the relic density. It enhances annihilation and favors $\gamma, e^+, \bar{p}$ indirect detection. A lighter scalar Higgs H also increases direct detection rate. High $\tan\beta$ also enhances the splitting in Isospin= 1/2 sfermion mass matrix favoring LHC discovery *e.g* in case of lighter $\tilde{b}$ squark, whereas lighter stau $\tilde{\tau}$, H, A favor their production in a Linear Collider as it is clearly shown in Fig. 5.

4.2 Gaugino sector

4.2.1 The wino mass : $M_2|_{GUT}$

We show in Fig. 6 the effects of non–universality of the gaugino breaking mass term M_2. Other authors in the literature has already underlined the phenomenological and cosmological effects of such pattern of the breaking mass terms [134] Decreasing $M_2|_{GUT}$ increases the wino content of the neutralino which decreases strongly the relic density [30, 29, 28]. A near WMAP value is obtained for an almost equal amount of bino and wino *i.e* $M_1 \simeq M_2$ at the SUSY breaking scale, requiring $M_2 \simeq 0.6 m_{1/2}$ at the GUT scale [29]. Direct detection is favored through better couplings in the diffusion cross section (no $\tan\theta_W$ suppression with regard to bino coupling). Gamma, positron and antiproton indirect detections are also made easier because of the large fluxes coming from strong annihilation $\chi\chi \to W^+W^-$ when $m_\chi > m_W$ and the enhancement of the $\chi\chi A$ coupling for the s–channel A exchange. Concerning neutrino indirect detection, the wino component has no effect on capture in the Sun but the annihilation can give harder neutrino spectrum from W^+W^- decays. The situation at LHC is the same as for the universal case. The Linear Collider perspective is very good because of lighter neutralino and chargino through their wino component. The $\chi\chi_2^0, \chi^+\chi^-$ can thus be produced for higher values of $m_{1/2}$. One has to be aware that a smaller $M_2/m_{1/2}$ ratio at GUT scale can lead to $\chi\chi_1^+$ and $\chi\chi_2^0$ degeneracies which can affect the detection procedure. It is important to keep in mind that the numerical computation of Ωh^2 is very sensitive to the wino fraction in χ. Experiment perspectives are thus weak in regions of parameter space satisfying WMAP constraints, with low M_2 at GUT scale. We show on Fig, 6 the results for $M_2/m_{1/2} = 0.6$ at GUT scale but we mention that for $M_2/m_{1/2} = 0.55$ the *whole* $(m_0, m_{1/2})$ plane has $\Omega_\chi h^2 < 0.1$ but the regions accessible by dark matter experiments corresponds to regions where the relic density is too low ($\Omega_\chi h^2 < 0.03$). One has to increase $m_{1/2}(m_\chi)$ to obtain a relic density satisfying WMAP constraints with smaller $M_2/m_{1/2}$ ratio.

4.2.2 The gluino mass : $M_3|_{GUT}$

Fig. 7 shows the effects of non–universality of the gaugino breaking mass term M_3. The gluino mass parameter influences considerably the MSSM spectrum through the Renormalization Group Equations (see for instance [11] for a review on the subject). Decreasing M_3 decreases squark masses, increases the up-type Higgs mass M_{Hu}^2 at low energy where it becomes less negative, and decreases the down-type Higgs mass M_{Hd}^2 which implies lighter $m_{A,H}$

and an increase of the Higgsino content of neutralinos and charginos. That can be easily understood looking at the approximate tree level relations :

$$\mu^2 \simeq -M_{H_u}^2 - 1/2 M_Z^2 \quad \text{and} \quad m_A^2 \simeq M_{H_d}^2 - M_{H_u}^2 - M_Z^2 \tag{4.15}$$

As a result, relic density constraints are more easily satisfied than in the universal case : both $\chi\chi \xrightarrow{A} b\bar{b}$ annihilation (higher coupling *and* lighter A which can open the A funnel) and focus point region with the $\chi\chi \xrightarrow{Z} t\bar{t}$ annihilation process are enhanced. Direct detection gets advantage of higher couplings $z_{11}z_{13}$ and lighter scalar Higgs H. The higher Higgsino fraction favors neutrino indirect detection through the coupling in $\chi q \xrightarrow{Z} \chi q$ of the capture rate. Gamma, positron and antiproton indirect detection are favored by the annihilation enhancement. LHC gets strong potentiality enhancement because the squarks (especially the $\tilde{t_1}$) and gluinos are lighter than in the Universal case. Finally, the HA production at a 1 TeV Linear Collider is kinematically enhanced, H and A being lighter than in mSUGRA. $\chi^+\chi^-$ $\chi\chi_2^0$ production are also favored because a lower value of μ. As in the non–universal wino mass case, smaller $M_3|_{GUT}/m_{1/2}$ values can lead to $\chi\chi_1^+$ and $\chi\chi_2^0$ degeneracies, now through the Higgsino component, which constrains the detection but those regions have too small relic density driven by coannihilation to be really favored. These points are well illustrated in Fig. 7 for the ratio $M_3/m_{1/2} = 0.6$ at GUT scale [29]. Those kinds of models with light gluino mass are very interesting for SUSY detection and all neutralino dark matter detections and can be found in some effective string inspired scenarios [32,33,34].

4.3 Higgs sector

4.3.1 Up-type Higgs mass : $M_{H_u}|_{GUT}$

Fig. 8 shows the prospects of detection for $M_{H_u}/m_0 = 1.2$ at the GUT scale. Increasing the up-type Higgs mass M_{H_u} at the GUT scale has some common effects with the case described above when decreasing gluino mass as can be explicitly seen from Eq. 4.15. One has to notice that the sensitivity on this parameter is high, leading to a thiner region with interesting results and wider "no EWSB" area compared to the previous non universal gluino mass case. As was done in the gaugino sector [29] we varied continuously the non–universality in the Higgs sector at GUT scale (M_{H_u}/m_0 and M_{H_d}/m_0) and found for the up-type mass that the relevant value of the ratio leading to WMAP relic density is around 1.2 for $\tan\beta = 35$. With respect to the universal case, the mixed bino-Higgsino region is more important but the pseudo–scalar Higgs A is still too much heavy to open the on–shell $A-$pole channel. All kinds of dark matter detections are thus possible in the resulting mixed bino-Higgsino region as well as chargino production in a future Linear Collider where HA pairs can also be produced. LHC gets no enhancement in squark and gluino production but covers a wide part of the not excluded remaining plane.

4.3.2 Down-type Higgs mass : $M_{H_d}|_{GUT}$

Fig. 9 illustrates the case of non–universality $M_{H_d}/m_0 = 0.4$ at GUT scale. Indeed, a ratio $M_{H_d}/m_0 < 1$ can have interesting phenomenological consequences concerning the different detection rates. By decreasing the down-type Higgs mass, M_{H_d} at GUT scale, one essentially decreases $m_{A,H}$ as can be seen in Eq. 4.15. The excluded region at high values of m_0 results from negative mass of the pseudo-scalar in addition to problem of not realizing the EWSB. The A–pole can be open more easily giving a corridor with interesting relic density within the WMAP bounds. In this corridor, neutralino annihilation is important, increasing the perspective of discovery through γ, e^+ and $\bar{p}$ indirect detection. The low value of m_{H_d} gives also good direct detection rates but we have to keep in mind that we have nearly bino neutralino in all the remaining region of the $(m_0, m_{1/2})$ plane such that $\chi\chi H$ coupling is suppressed. For the same reason of small Higgsino fraction, neutrino telescopes are strongly disfavored for those kinds of models. The LHC have an equivalent potentiality of discovery than in mSUGRA, but cover a wider area of the parameter space. Only the Higgs production HA is enhanced at the Linear Collider compared to the universal case while gaugino-Higgsino neutralino and chargino productions are suppressed.

5 Summary-Conclusion

Dark matter experiments and collider searches will be a major step to probe the possibility of low energy supersymmetry and neutralino dark matter in the Minimal Supersymmetric Standard Model. The possible correlations between (absence of) signals of different kinds of detection will bring many informations on models and scenarios both for supersymmetry and astrophysics.

We summarize hereafter the links between the different possibilities to fulfill WMAP constraint, the parameters involved and the kind of detection concerned.

The $\chi\tilde{\tau}(\tilde{t})$ coannihilation region is typically difficult for dark matter detection. It can be possible for a huge direct detection experiment if $m_{\tilde{\tau}}$ and m_H are correlated (low $m_{\tilde{\tau}}$ to favor the coanihilation process and light H to favor direct detection scattering) as well as for γ indirect detection in the case of favorable galactic profile (with a stronger cusp than in the NFW profile). The LHC can be of interest through $\tilde{q}\tilde{q}$ if $m_{\tilde{q}}$ is correlated to $m_{\tilde{l}}$ and the ILC through $\tilde{\tau}\tilde{\tau}$ to probe the $\tilde{\tau}$ coannihilation region.

The Higgs funnel region $\chi\chi \xrightarrow{A} b\bar{b}(\tau\bar{\tau})$ is favored with respect to the universal case for non universal M_3 or M_{H_u} or M_{H_d}. Direct detection is concerned but large m_A value need also a coupling enhancement through the Higgsino fraction of the neutralino. The γ $(e^+, \bar{p})$ indirect detection follow this annihilation process. However the absolute potentiality depends on astrophysics hypothesis. The LHC situation depends on $m_{\tilde{q},\tilde{g}}$ with regard to m_A and for the ILC, $\chi\chi_2^0$ and HA productions are favored up to energy limitation.

The Hyperbolic Branch/Focus Point with mixed bino-Higgsino χ at high m_0 values and especially non universal M_3 or M_{H_u} parameters is the more interesting region concerning the DM searches. Direct detection can bring informations on the nature of the neutralino by correlations between spin dependent/independent experiments as well as through correlations with neutrino telescope. $\gamma(e^+, \bar{p})$ Indirect detections of γ, e^+ or $\bar{p}$ are favored through the enhancement of annihilation processes. Moreover, this region of mixed neutralino is the only one accessible by a neutrino telescope for a signal coming from the Sun (a km^3 size telescope will probe up to $m_\chi \sim 600$ GeV). The chargino production in e^+e^- collider as well as gluino production for LHC are the relevant processes but become difficult for very high values of the breaking mass terms, keeping in mind that those regions have $\delta_\mu^{\text{susy}} = 0$.

Finally a mixed bino-wino χ is very sensitive to a non–universal M_2 parameter. The wino component enhances dark matter rates (Ωh^2 is very sensitive to the wino fraction). The LHC can be of interest if the gluino mass is correlated to the wino mass and wino-like neutralino/chargino production in ILC is possible up to $m_{\chi(\chi_1^+)} \simeq 500$ GeV.

However, even if a part of the supersymmetric spectrum is discovered at LHC, it will be difficult to measure precisely the properties of the particles entering in the relic density computation. Both types of data (astroparticle and accelerator physics) will thus be needed to extract more complete informations about the underlying model.

Whereas the Focus Point (FP) region characterized by heavy scalars will be more easily probed by dark matter searches projects due to the nature of the neutralino, the region with heavy gaugino and light sfermions will be more accessible by collider experiments. Since dark matter signals give few informations on the nature of the dark matter and since new physics collider signals could not be linked directly to dark matter ones, deeper informations on both supersymmetry and astrophysics hypothesis can thus be obtained by correlation of the different signals or absence of signal.

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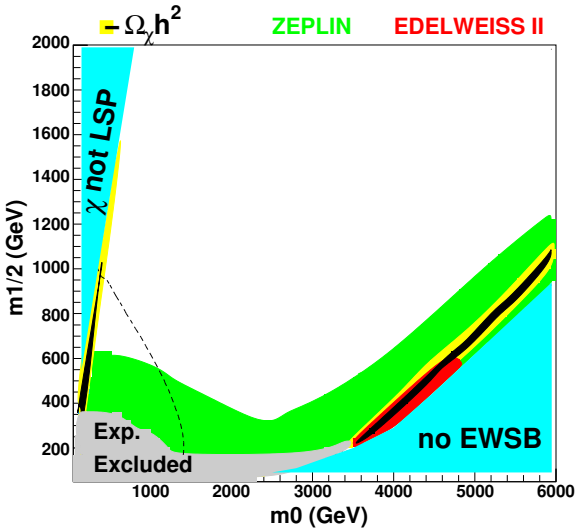

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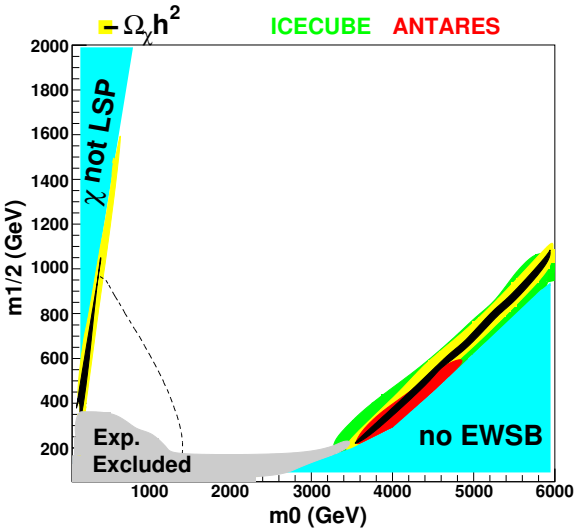

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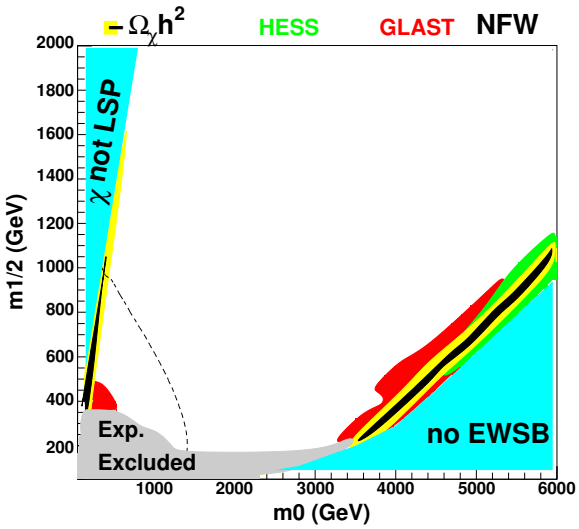

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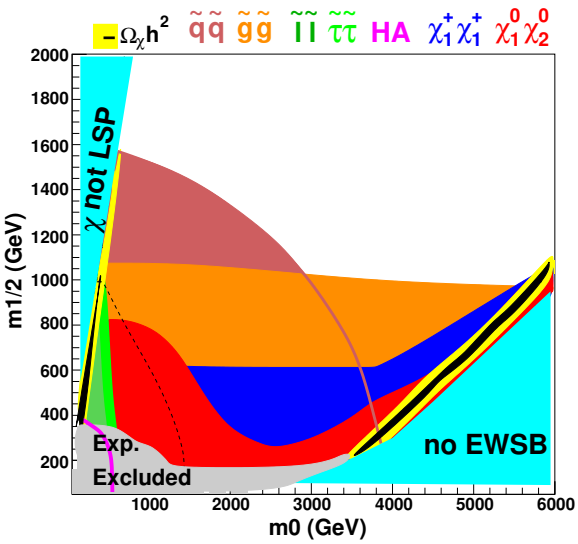

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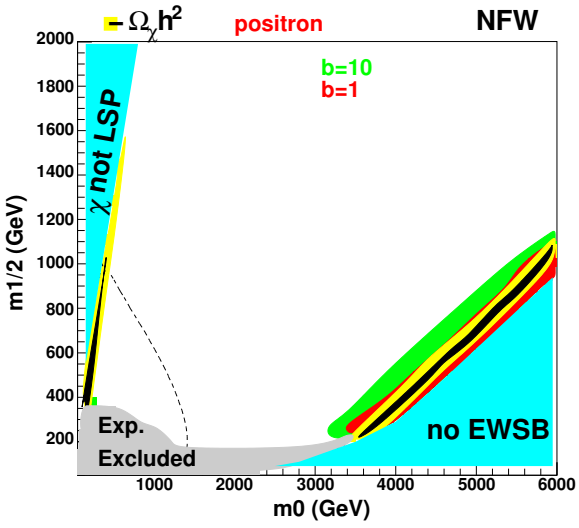

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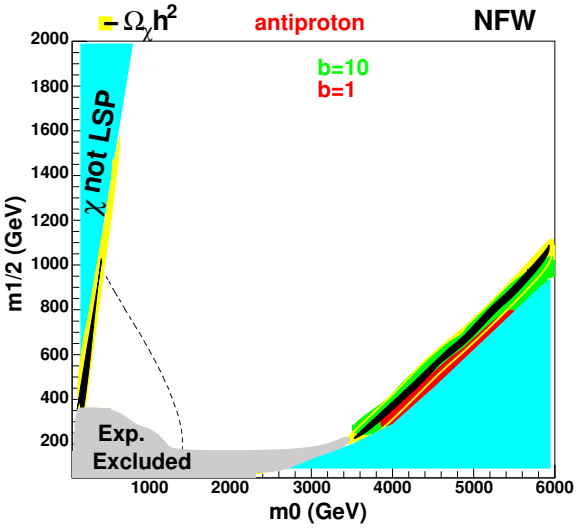

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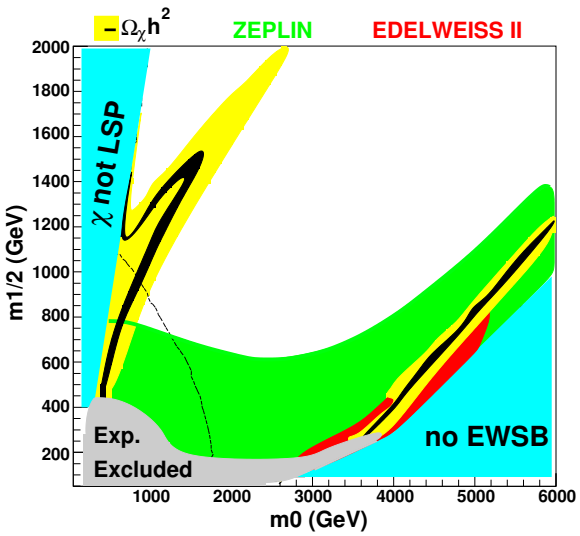

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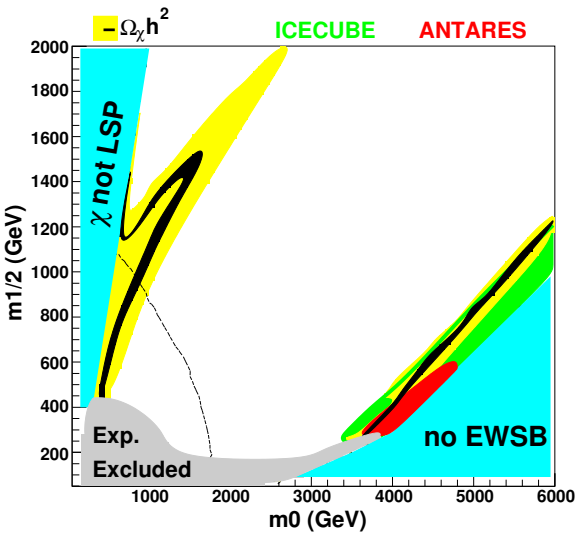

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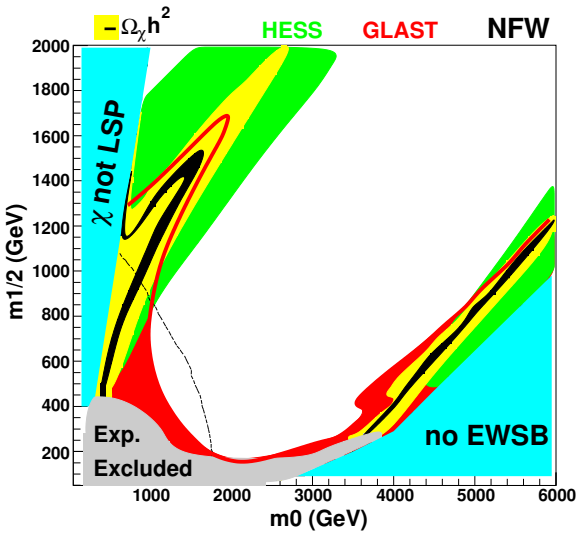

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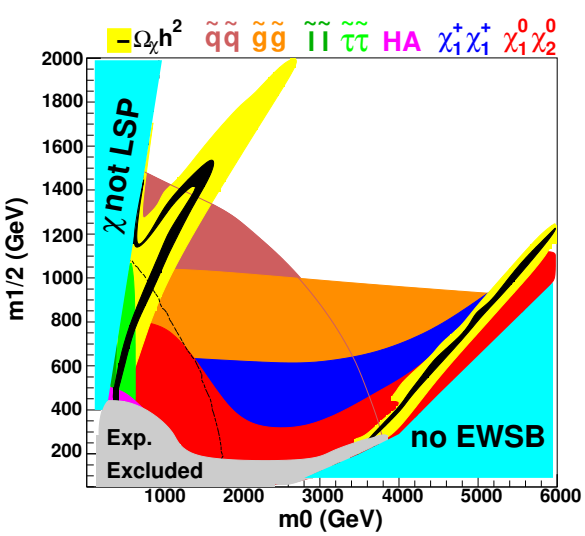

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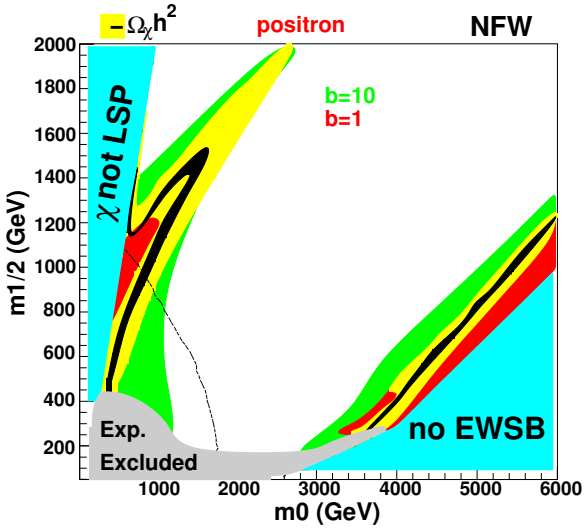

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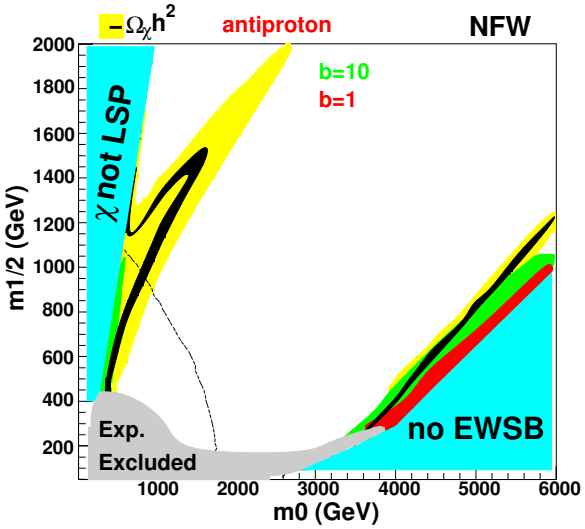

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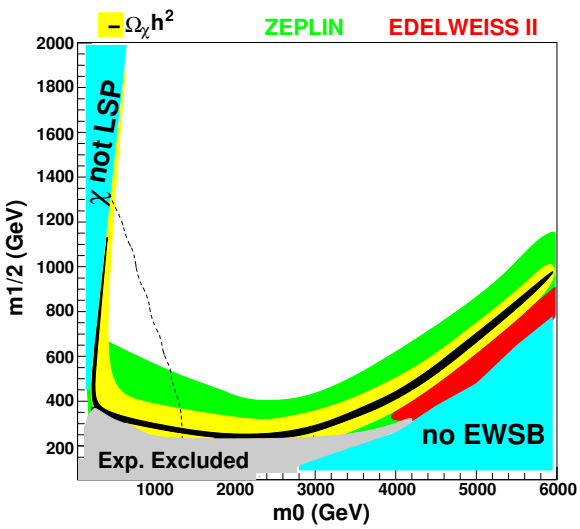

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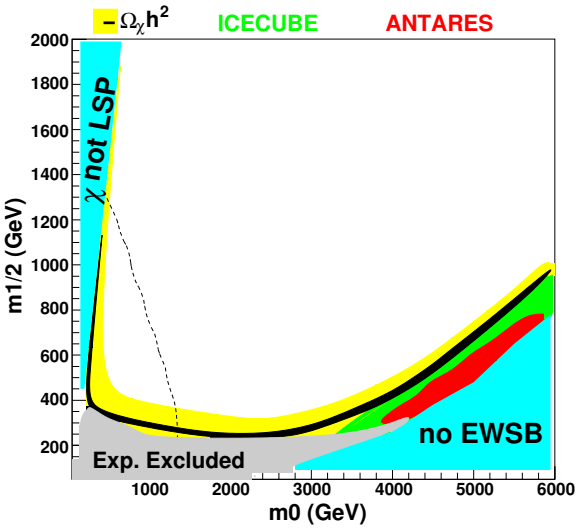

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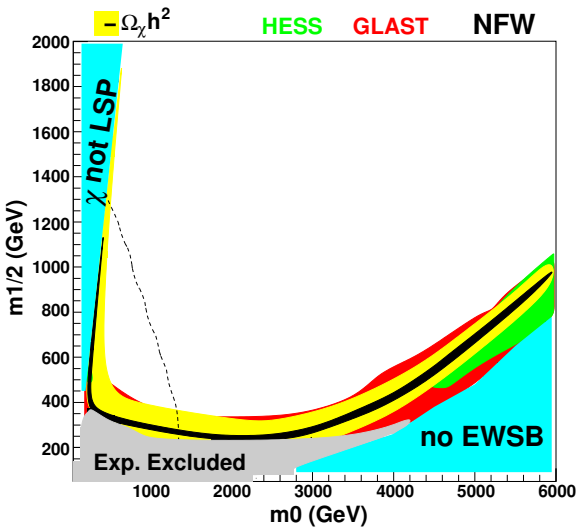

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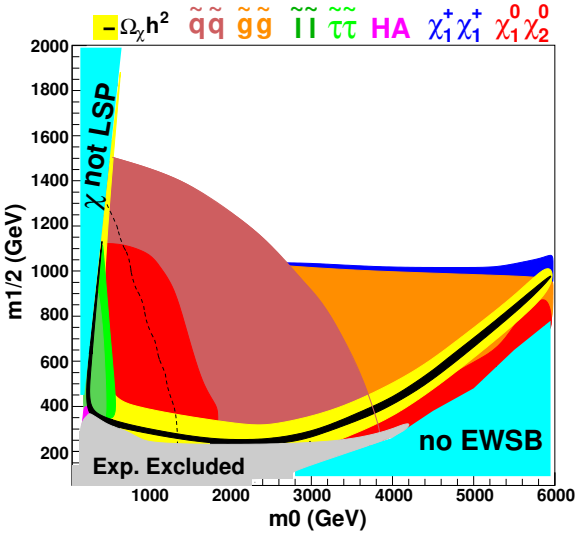
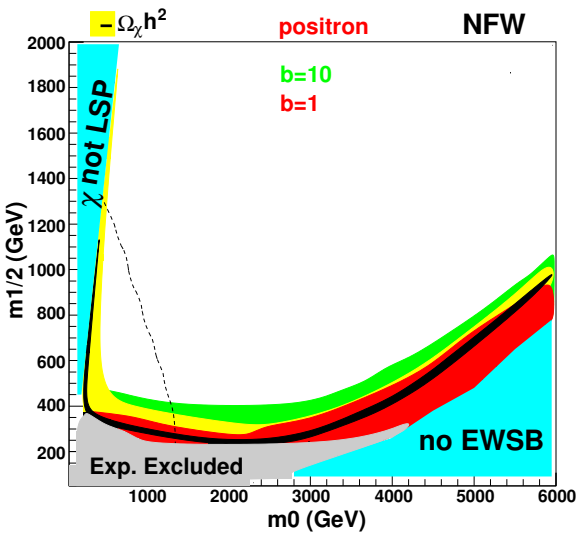


d) Collider production (LHC,ILC)



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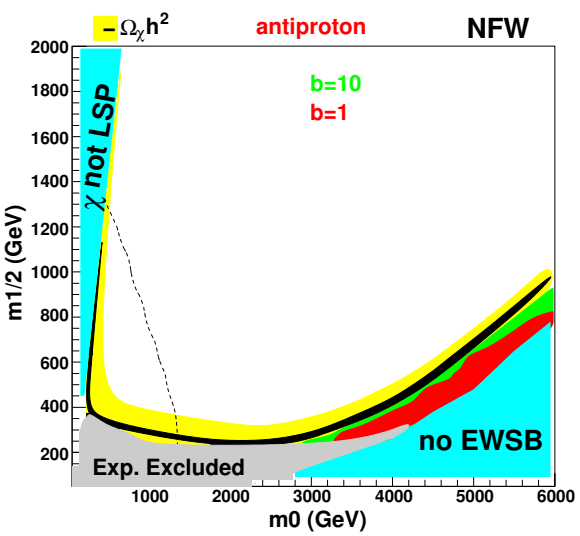

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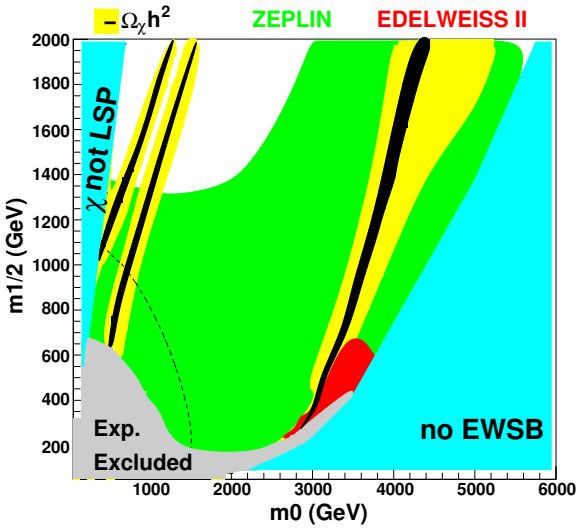

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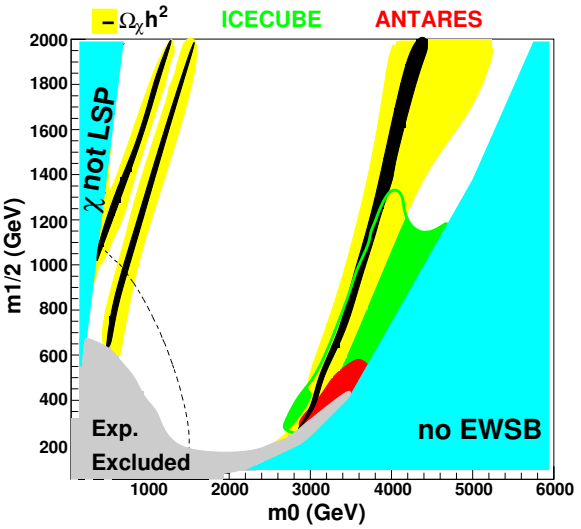

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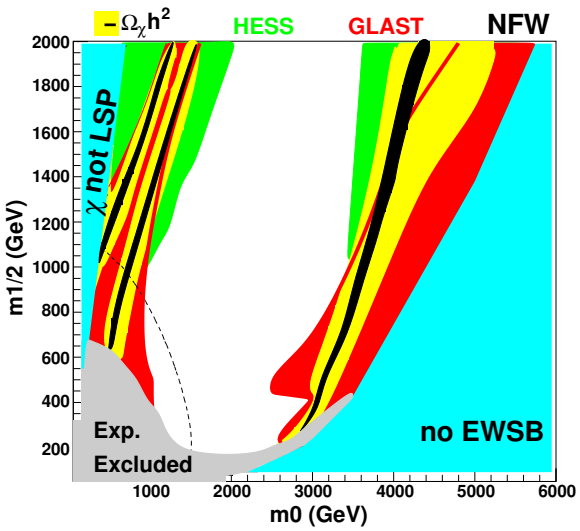

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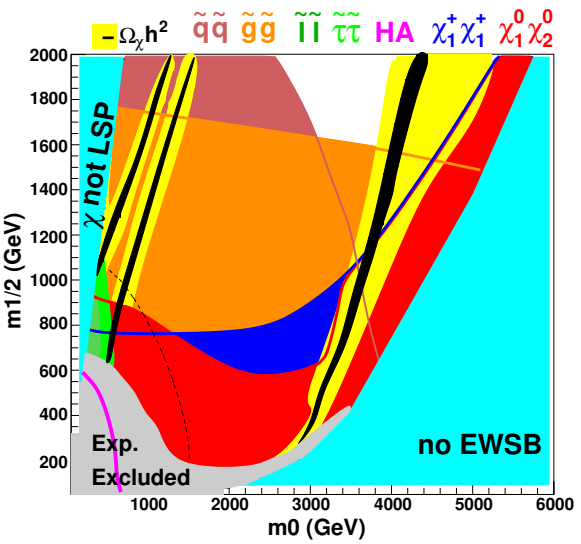

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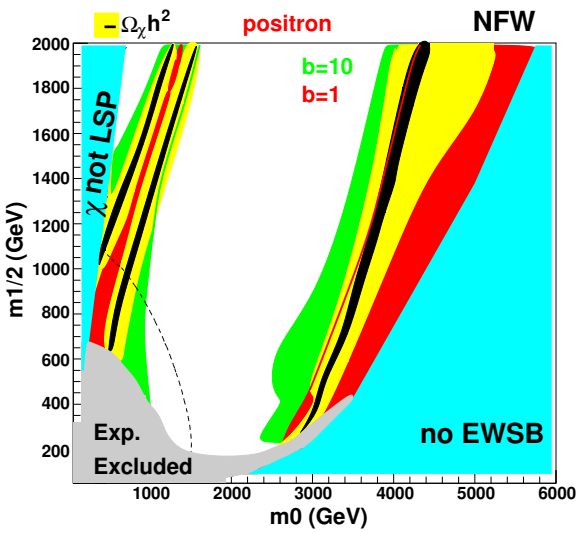

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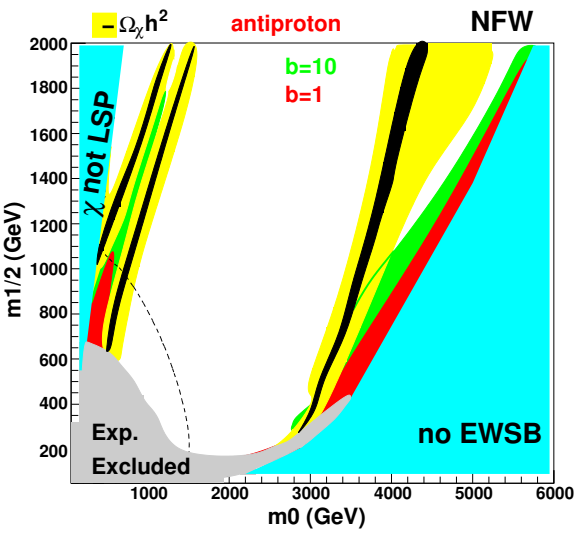

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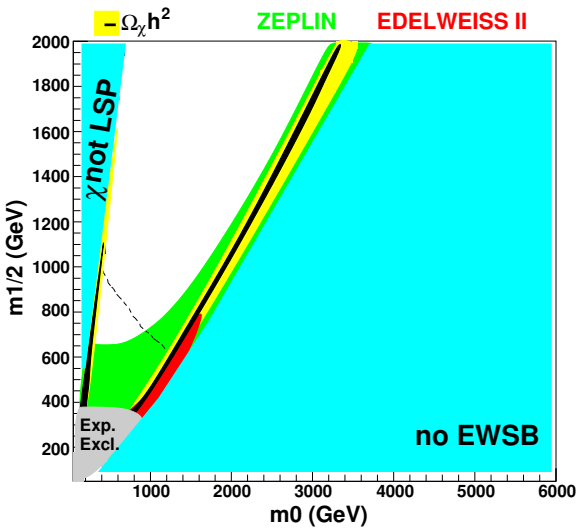

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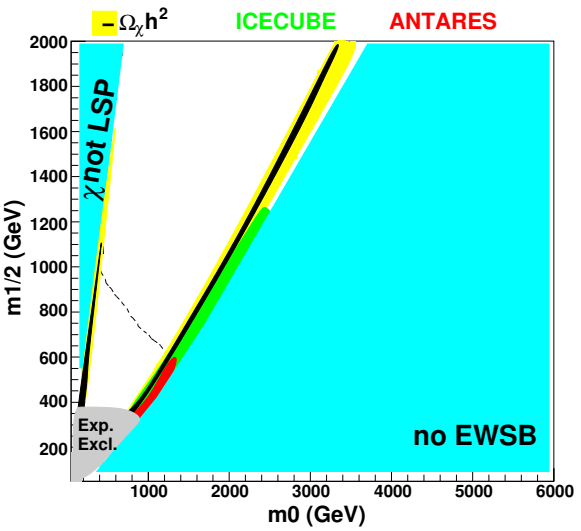

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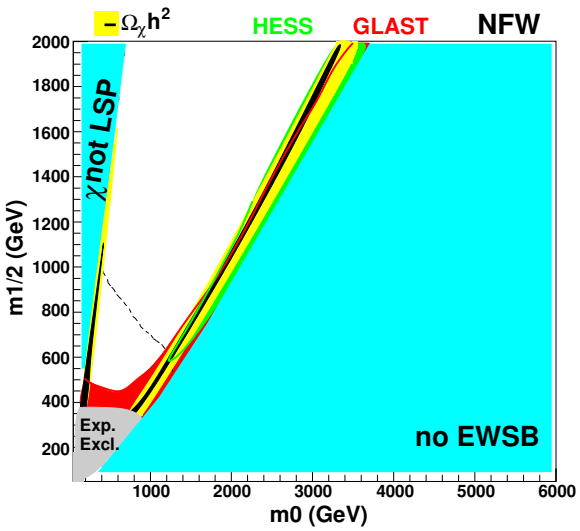

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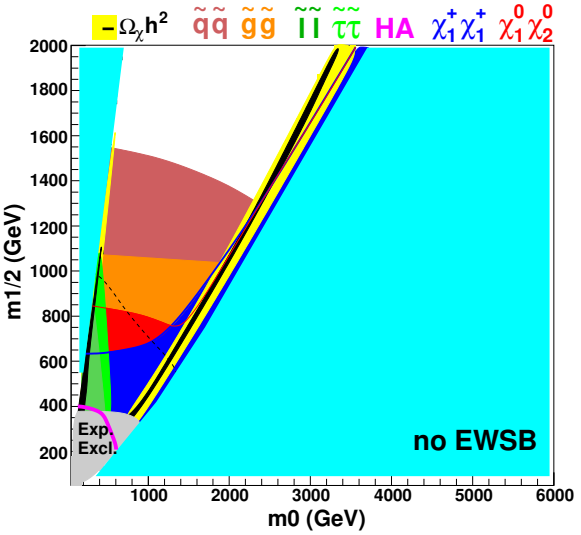

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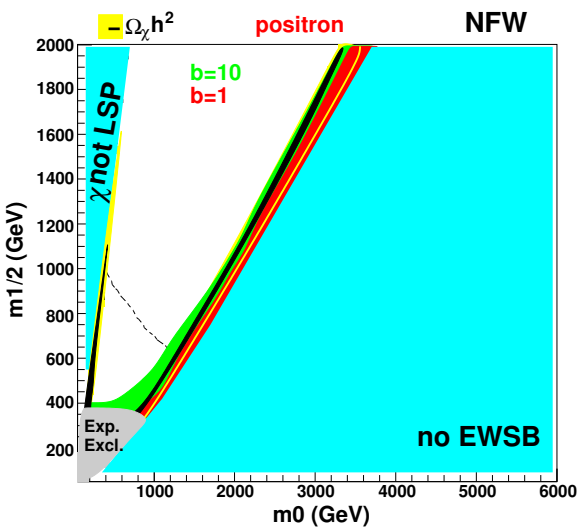

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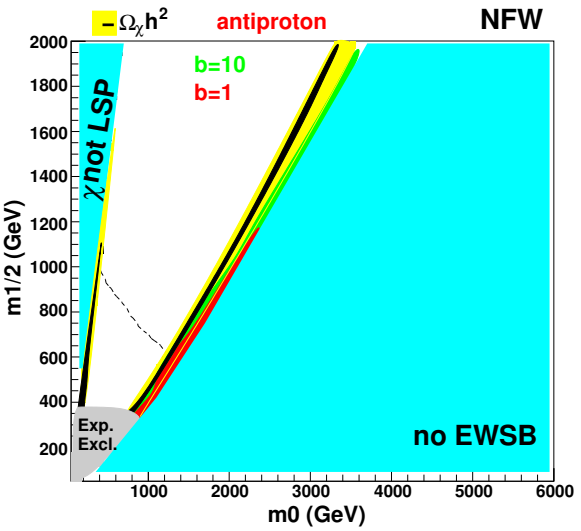

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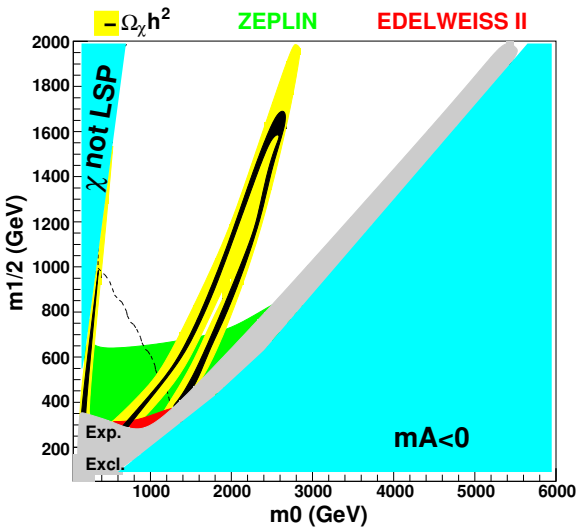

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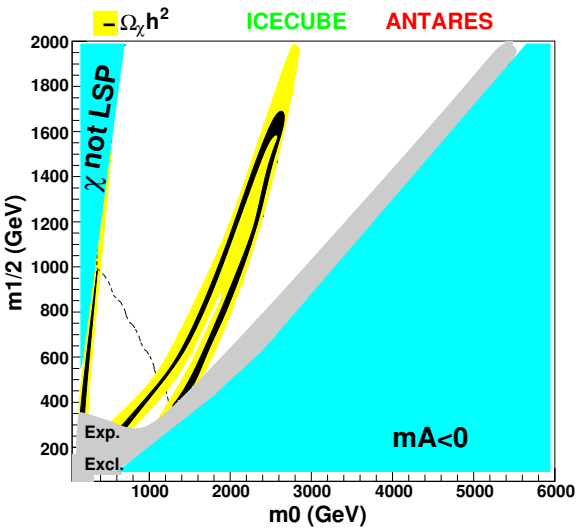

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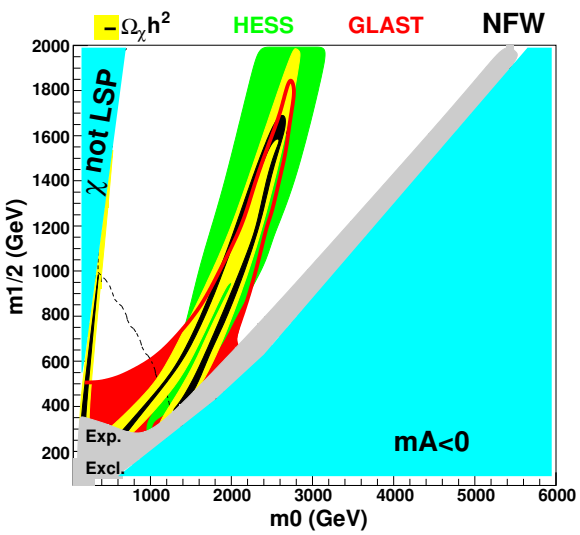

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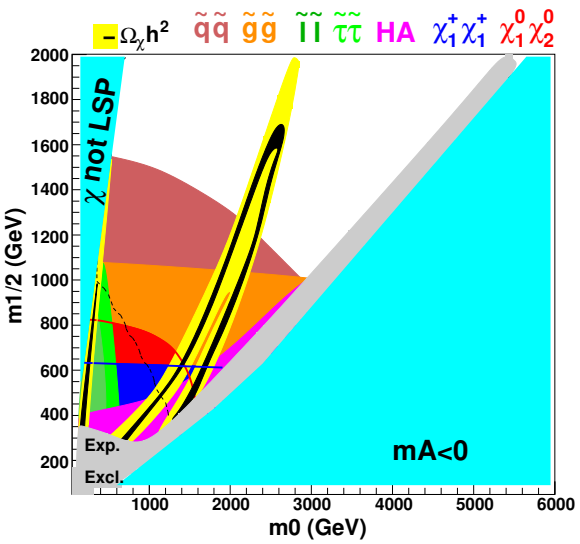
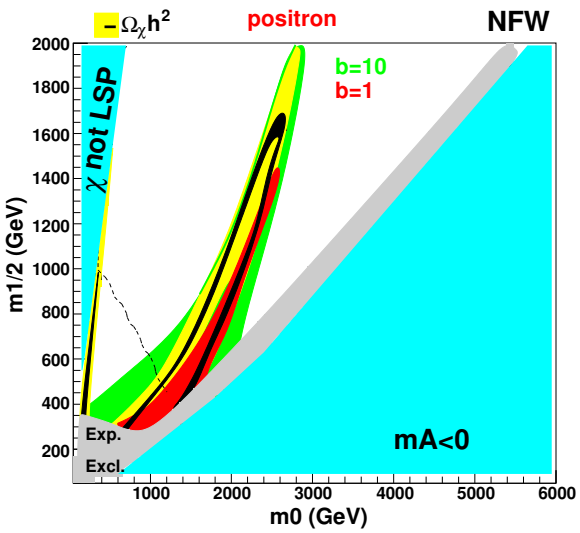


d) Collider production (LHC,ILC)



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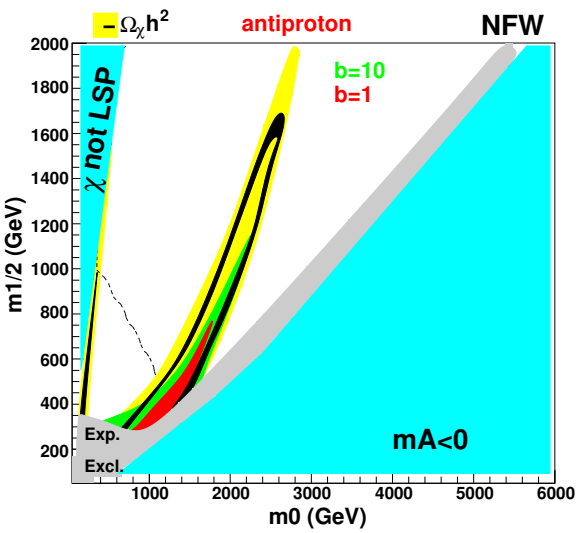

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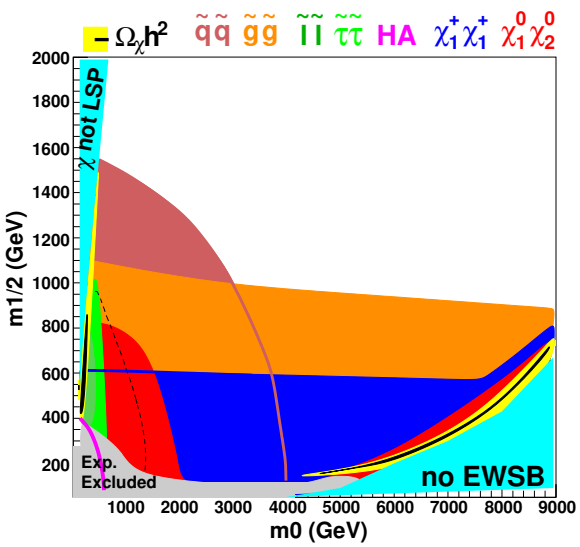
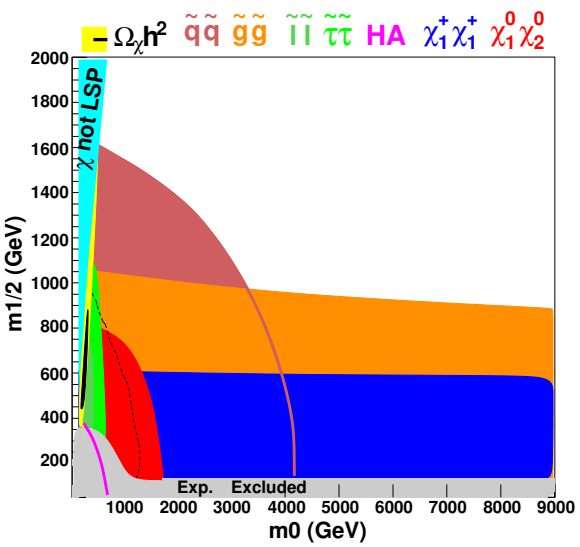
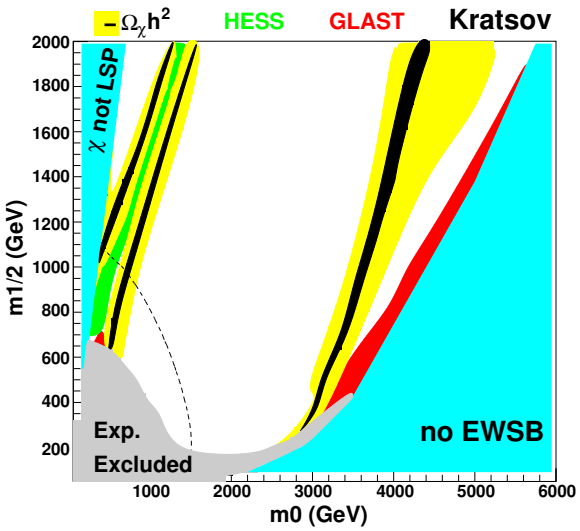


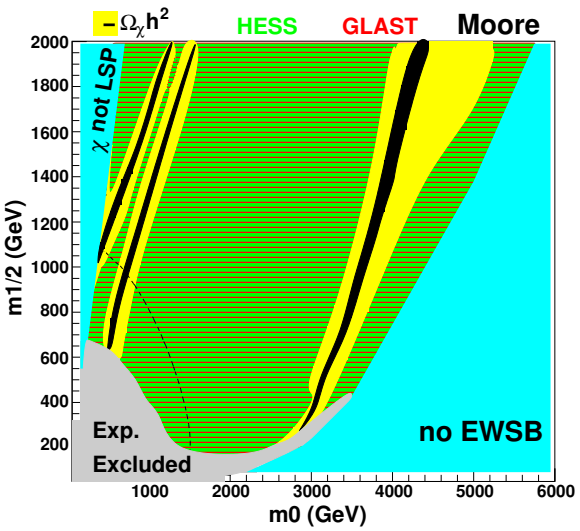
a) $m_t = 178$ GeV



b) $m_t = 182$ GeV



c) γ Indirect Detection : Kravtsov profile



d) γ Indirect Detection : Moore profile

Fig. 10. Effect of m_t=178 GeV in a) and m_t=182 GeV in b) on LHC and ILC performances in the universal case (to be compared with Fig. 4d)). Halo profile influence on γ indirect detection. $A_0 = 0$, $\tan\beta = 35$, $\mu > 0$ for non universal gluino mass $M_3|_{GUT} = 0.6 m_{1/2}$ with a Kravtsov profile in c) and Moore profile in d) (to be compared with the NFW profile case Fig. 7c))